Radiocarbon reservoir effects in human bone collagen from northern Iceland

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Abstract

Human bone collagen from a series of Icelandic human pagan graves was radiocarbon (^{14}C) dated to aid understanding of early settlement (*landnám*) chronologies in northern Iceland. These individuals potentially consumed marine protein. The ^{14}C age of samples containing marine carbon requires a correction for the marine ^{14}C reservoir effect. The proportion of non-terrestrial sample carbon was quantified via measurement of carbon stable isotopes ($\delta^{13}C$) using a simple mixing model, based on $\delta^{13}C$ measurements of archaeofaunal samples. Non-terrestrial carbon was also quantified in six pig bones from the archaeofaunal dataset. Assuming all non-terrestrial carbon in human and pig bone collagen was marine-derived, calibrated age ranges calculated using a mixed IntCal09/Marine09 calibration curve were consistent with an early settlement date close to *landnám*, but several samples returned pre-*landnám* age ranges. Measurements of nitrogen stable isotopes ($\delta^{15}N$) strongly suggest that many of the human bone collagen samples contain freshwater diet-derived carbon. Icelandic freshwater systems frequently display large freshwater ^{14}C reservoir effects, of the order of 10,000 ^{14}C years, and we suggest that the presence of freshwater carbon is responsible for the anomalously early ages within our dataset. In pig samples, the majority of non-terrestrial carbon is freshwater in origin, but in human samples the proportion of freshwater carbon is within the error of the marine component (± 10%). This presents a major obstacle to assessing temporal patterns in the ages of human remains from sampled graves, although the majority of grave ages are within the same, broad, calibrated range.

Keywords

Radiocarbon reservoir effect, freshwater, marine, Iceland, pagan grave

1. Introduction

The pristine landscape of Iceland was colonised from AD 871 ± 2 (Grönvold et al., 1995) as part of the Viking (early Norse) *landnám* across the North Atlantic (Dugmore et al., 2005). Post- *landnám* Icelandic landscapes experienced large-scale human environmental impacts, climatic variation and societal changes (Vésteinsson, 1998, 2000; Buckland, 2000; Andrews et al., 2001; Dugmore et al., 2007; Lawson et al., 2007), yet a lack of detailed contemporary historical records means archaeological and palaeoenvironmental data are crucial for studying this initial settlement period. A key question is verifying the rapid timing of inland settlement; midden deposits from various excavated settlements are in direct contact with the *landnám* tephra at Mývatnssveit (i.e. the region surrounding Lake Mývatn; Figure 1), c. 60 km from the coast (McGovern et al., 2006a, 2007). This is paralleled by a considerable number of pagan graves running from the north Icelandic coast to the interior highlands (Figure 1; Gestsdóttir, 1998; Eldjárn, 2000; Roberts, 2008). These pagan graves are likely to contain early inhabitants of Iceland, pre-dating the Christian conversion around AD 1000. To establish if these interments represented a single age range, or spatially variable ages dependent on the distance from the coast, bone collagen from human and animal bone from the graves was radiocarbon (^{14}C) dated as part of the 'Landscapes circum-*landnám*' project (Edwards et al. 2004; Dugmore et al. 2005).

A major consideration when ^{14}C dating human bone is whether any sample carbon (C) originated from a non-terrestrial reservoir. Terrestrial carbon sources include protein from domesticated land mammals (e.g. cattle), while non-terrestrial carbon sources include marine and freshwater fish and birds, and marine mammals (e.g. seals). The ^{14}C age of samples from the atmospheric and terrestrial biospheric carbon reservoirs are calibrated to a calendar year age span with the IntCal09 atmospheric curve (Reimer et al., 2009), but the ^{14}C age of samples from other C reservoirs can be offset from that of contemporaneous atmospheric/terrestrial samples. This offset is known as a 'reservoir effect' and must be corrected for in order to produce accurate calibrated age ranges. The marine ^{14}C reservoir effect (MRE) results from radioactive decay of ^{14}C atoms during deep ocean water circulation (Stuiver and Braziunas, 1993; Ascough et al., 2005). In 100% marine samples, the MRE is quantified by calibration with the separate Marine09 curve, plus an additional local offset from the global average MRE, known as ΔR (Stuiver and Braziunas, 1993; Ascough et al., 2005; Reimer et al., 2009). The ^{14}C age of bone collagen is a time-averaged integration of ^{14}C in dietary protein consumed over ~10-30 years prior to death (Ambrose and Norr, 1993; Hedges et al., 2007), meaning ^{14}C ages from individuals that consumed large quantities of

marine protein appear older than those of contemporaneous individuals that consumed 100% terrestrial diets (cf. Tauber, 1983; Yoneda et al., 2002; Bayliss et al., 2004). The importance of marine resources to Norse communities, even when located many kilometres inland (Einarsson, 1994; McGovern et al., 2006a), means that ^{14}C dating in the Viking Age North Atlantic can be problematic (e.g. Arneborg et al., 1999; Barrett et al., 2000; Ascough et al., 2006; Sveinbjörnsdóttir et al., 2010). Samples in this study were therefore assessed to identify ^{14}C measurements affected by the MRE and correction applied to the ages where possible.

^{14}C ages of bone collagen containing both terrestrial and marine C can be calibrated with a mixed IntCal09 and Marine09 calibration curve (Bronk Ramsey, 1998). The amount of marine carbon in the sample must be quantified, usually via its $^{13}C/^{12}C$ stable isotope ratio ($\delta^{13}C$ value) (Coplen, 1995). Bone collagen $\delta^{13}C$ values predominantly reflect the $\delta^{13}C$ of dietary protein; this is significantly different for marine and terrestrial protein, where the $\delta^{13}C$ of terrestrial herbivore tissue is typically c. -23 to -20‰ (e.g. DeNiro and Epstein, 1978), compared to c. -15 to -17‰ for marine fish (e.g. Ambrose and Norr, 1993; Jim et al., 2004; DeNiro and Epstein, 1978; Hobson, 1990). The proportion of marine C in bone collagen of terrestrial omnivores can be assessed on a mass balance basis:

$$\delta_M = f_{Terr}\delta_{Terr} + f_{Mar}\delta_{Mar}$$

Where:

δ_M = isotopic value of the mixture in the sample

f_{Terr}, f_{Mar} = fraction of terrestrial and marine C, respectively (where $f_{Terr} + f_{Mar} = 1$)

δ_{Terr}, δ_{Mar} = isotope values of terrestrial and marine C, respectively

The simplest approach to calculate f_{Mar} is via a linear mixing model, as previously used to successfully calibrate ^{14}C ages of human bone collagen, including Viking period samples from the North Atlantic (cf. Arneborg et al., 1999; Sveinbjörnsdóttir et al., 2010). This approach requires $\delta^{13}C$ end-member values for the bone collagen of a consumer existing on i) 100% terrestrial protein, and ii) 100% marine protein. These can be obtained from individuals known to have existed on the diets in question, or from measurements of dietary resources that are corrected for the diet-consumer trophic level fractionation. In either case, the accuracy of the calculated marine C proportions depends upon the selected end-member values (Dewar and Pfeiffer, 2010), which must be obtained from the same geographical region as the samples themselves (Hobson, 1999). This is because plant $\delta^{13}C$ values, and hence herbivore tissue $\delta^{13}C$ values, show wide geographical variation (McCarroll and Loader,

2004). In this study we measured the $\delta^{13}C$ in geographically and temporally relevant samples of major terrestrial and marine protein sources. For a single species population accessing the same food resources, uncertainty in stable isotope-based dietary reconstructions can result from the range in isotopic values. This appears to be a consequence of individual feeding preferences and variable diet-consumer isotopic enrichments, but the resulting variation is not well quantified (Hobson and Schwartz, 1986; Bocherens and Drucker, 2003). Multiple samples from several individual sites were measured in order to assess the likely range in $\delta^{13}C$ values within the terrestrial and marine resource groupings and hence obtain some measure of the uncertainty that should be applied to our calculated proportions of sample marine C.

Calibration of sample ^{14}C ages from North Iceland is complicated by the fact that freshwater resources potentially consumed by the Icelandic settlers often display very large freshwater ^{14}C reservoir effects (FREs). This is due to the release of ^{14}C-depleted carbon during geothermal activity (Sveinbjörnsdóttir et al., 1992, 1995 Ascough et al., 2007, 2010), and FREs can also vary by several thousand ^{14}C years within a single freshwater system, meaning that accurate ^{14}C age correction of affected samples is virtually impossible (Ascough et al., 2011). Freshwater resources (comprising fish bones and waterfowl eggshell fragments) are abundant at many archaeological sites in the study region; for example, sites within Mývatnssveit show a very high percentage of freshwater fish (Arctic char and brown trout) in their archaeofauna (McGovern et al., 2006a, 2007). This makes it important to assess the potential for freshwater C incorporation into the samples included in the study.

The $\delta^{13}C$ of freshwater organisms is highly variable between different freshwater systems (Post, 2002). Where freshwater $\delta^{13}C$ values overlap with those of organisms within another C reservoir, it may not be possible to differentiate between contributions of resources from these two reservoirs within the tissues of a consumer (Hobson 1990). Freshwater biota $\delta^{13}C$ values frequently overlap with the $\delta^{13}C$ values of terrestrial biota (Hobson, 1990; Lanting and van der Plicht, 1998). In the study region, $\delta^{13}C$ values of freshwater biota are in the range -12 to -15‰. These values overlap with those of marine resources, and they are distinct from those of terrestrial biota (Ascough et al., 2010; Russell et al., 2011). Although it is therefore possible to discriminate between terrestrial and non-terrestrial sources within human bone in the study region, it is possible that a proportion of the non-terrestrial component could in fact be derived from freshwater resources. The $\delta^{15}N$ value of consumer bone collagen also reflects that of dietary protein, with an offset of up to +5.3‰ per trophic level (Minagawa and Wada, 1984; Cabana and Rasmussen, 1994, 1996). The large number of

trophic levels in marine ecosystems typically results in $\delta^{15}N$ values for marine fish in the range ~+11 to +15‰ (Becker et al., 2007). Analyses of freshwater fish in the study region suggest relatively simple ecosystems with $\delta^{15}N$ values similar to those of some terrestrial herbivores at ~6‰ (Ascough et al., 2010). We therefore attempted to use the stable nitrogen isotope ratio ($^{15}N/^{14}N$, expressed as $\delta^{15}N$) of bone collagen to identify any significant freshwater dietary component in the samples not evident from the $\delta^{13}C$ analyses.

2. Methodology

2.1 Sample material

Human bone

Radiocarbon (^{14}C) age and stable isotope measurements were made on the bone collagen from seven human individuals from seven burial sites in North Iceland (Table 1; Figure 1). Samples were obtained from the Icelandic National Museum archives and the constituent sites ranged from the coast (Grásíða) to approximately 100 km inland (Suðurárbotnar). Previously published ^{14}C results on human bone collagen from four pagan burials (Gautlönd, Grímsstaðir, Ytri-Neslönd and Glaumbær) that also contained material considered to be wholly terrestrial (McGoven et al., 2007; Ascough et al., 2010), were also included in the dataset.

Archaeofaunal remains: isotope baselines

No archaeofaunal remains were available from the human grave sites, with the exception of horse or dog bone that was interred with human burials at Gautlönd, Grímsstaðir, Ytri-Neslönd and Glaumbær (ibid.). Stable isotope measurements ($\delta^{13}C$ and $\delta^{15}N$) were therefore made on bone collagen from 18 cows (*Bos taurus*), 35 caprines (*Capra aegagrus hircus*/*Ovis aries*), and 22 pigs (*Sus sp*.) from four excavated sites in Mývatnssveit: Undir Sandmúla (McGovern, 2005), Sveigakot (Vésteinsson, 2002), Hofstaðir (Lucas, 2010) and Hrísheimar (Edvardsson and McGovern, 2007). These were chosen as representative of the major terrestrial, marine and freshwater resources dietary resources likely to have been available to the human individuals discussed above.

Archaeofaunal analysis of remains from Undir Sandmúla, Sveigakot, Hofstaðir and Hrísheimar indicate the presence of the full range of *landnám* age domestic animals, including cattle, sheep, goats, horses and pigs (McGovern et al., 2007). While for taphonomic reasons, preservation potential of fish bone is limited at Undir Sandmúla, marine and freshwater fish

form a significant component of midden deposits at Sveigakot, Hofstaðir and Hrísheimar, reflecting the importance of wild resources within the Norse palaeoeconomy, in which fish are the most common wild taxa (McGovern et al., 2006a, 2006b, 2007). The proportions of taxa vary somewhat between sites and between different phases at individual sites, but an overall regional trend is apparent in animal management strategy, with an increasing focus on sheep and cattle during the tenth century (McGovern et al., 2006a, 2007).

The sampled contexts (Table 2) dated to between the 9th to 11th centuries AD on stratigraphic grounds and tephrochronology, is confirmed by ^{14}C measurements from the archaeological sites. Previously published values for 10 cows, 6 pigs, Arctic char and brown trout from Hofstaðir and Hrísheimar (Ascough et al., 2007, 2010) are also included in the dataset. The domestic mammals included adult, juvenile and neonatal individuals, identified via zooarchaeological analysis. While, δ^{13}C and δ^{15}N values are available for seal bone from Gásir on the north Icelandic coast (Ascough et al., 2007; Table 4), unfortunately measurements of Icelandic fish archaeofaunal samples were not available for inclusion. A sample of marine fish resources, likely to be representative of isotopic values of marine resources, was therefore obtained from the δ^{13}C and δ^{15}N values of Russell et al. (2011) for Atlantic cod bone recovered from Norse and medieval period sites in northern Scotland.

2.2 Analytical methods

Bone samples were prepared for ^{14}C dating and stable isotope measurement (δ^{13}C and δ^{15}N) by extraction of collagen following a modified Longin (1971) method. After cleaning of the sample surface with a Dremmel® fitted with an abrading disk, the bone was roughly crushed and immersed in cold 1M HCl until dissolution of the bone phosphate was complete (up to 96 hours). The acid solution was decanted and the collagen washed in reverse osmosis water and then placed in further reverse osmosis water. Where necessary, a small amount of 0.5 M HCl was added to adjust the pH of the solution to 3. The solution was heated gently (approx 80 ºC) to solubilize the collagen (3-4 hours) and then cooled. The solution was filtered through Whatman GF/A glass fibre paper, and the collagen recovered by freeze-drying.

Measurements of sample %C and %N were made on a Costech elemental analyser (EA) (Milan, Italy), which was fitted with a zero-blank auto-sampler. These elemental abundances were then used to calculate sample CN ratios. Sample δ^{13}C and δ^{15}N measurements for palaeodietary analysis were made on a ThermoFinnigan Delta^{+} XL isotope ratio mass spectrometer (Thermo Finnigan GmbH, Bremen, FRG), which was linked to the

EA via a ConFlo III as described in Werner et al. (1999). Each sample run included a mix of samples, laboratory standards and blanks, with precision better than ± 0.2‰ (1σ) for $\delta^{13}C$ and better than ± 0.3‰ (1σ) for $\delta^{15}N$. Each $\delta^{13}C$ and $\delta^{15}N$ measurement for a sample was obtained from a single combustion of collagen from that sample in the EA. The isotope values are reported as per mil (‰) deviations from the VPDB and AIR international standards for $\delta^{13}C$ and $\delta^{15}N$ respectively.

For radiocarbon (^{14}C) measurements, CO_2 was obtained from collagen via combustion in sealed quartz tubes following the method of Vandeputte et al. (1996). The sample CO_2 was purified cryogenically and an aliquot taken for off-line $\delta^{13}C$ determination on a VG SIRA 10 isotope ratio mass spectrometer, using NBS 22 (oil) and NBS 19 (marble) as standards, with a precision of ± 0.1‰ (1σ) for $\delta^{13}C$. The $\delta^{13}C$ values thus obtained were used for normalization of measured sample $^{14}C/^{13}C$ ratios to values corresponding to $\delta^{13}C$ = -25‰ prior to calculation of ^{14}C ages (Stuiver and Polach, 1977; Donhaue et al., 1990). These values are presented in Tables 3 and 4. A 3 ml aliquot of the CO_2 was converted to graphite by the method of Slota et al. (1987) for ^{14}C measurement by AMS. Sample $^{14}C/^{13}C$ ratios were measured with carbon in the +1 charge state on the SUERC SSAMS at 245 keV.

2.3 Palaeodietary reconstruction and ^{14}C age calibration

End-members for the $\delta^{13}C$ linear mixing model were obtained from the averaged measured values for the marine and terrestrial archaeofaunal samples respectively, after application of a trophic level correction of +1‰ to account for tissue-diet $\delta^{13}C$ enrichment (e.g. Post, 2002). The proportion of marine carbon in a sample, calculated on this basis, is strongly dependent upon the selected endpoint values. Therefore, we sought to establish an appropriate error that could reasonably be applied to the calculated values. Values for % marine C in the human bone collagen samples were hence also calculated using a linear model based on i) the lowest and ii) the highest measured $\delta^{13}C$ values for the marine and terrestrial archaeofaunal sample groups. The difference between these two values was then used to represent the range in % marine C that could be calculated for the human samples using our faunal dataset.

In order to assess the potential for a freshwater dietary component in the human samples, we attempted to use $\delta^{15}N$ measurements as a diagnostic tool, as proposed by Cook et al. (2001). The $\delta^{13}C$ linear mixing model allowed us to identify a 'non-terrestrial' dietary component. This was assumed in the first instance to represent marine protein consumption (see above). However, this 'non-terrestrial' component also potentially included freshwater protein, on the basis of our archaeofaunal measurements. As the $\delta^{15}N$ of freshwater and

terrestrial systems in this region is substantially lower than that of marine resources, we undertook $\delta^{15}N$ measurements on all 'terrestrial' samples to identify whether the 'non-terrestrial' component within them was likely to be of freshwater origin. This was achieved by calculating the proportion of marine C in the samples with a $\delta^{15}N$-based linear mixing model and comparing the results with those obtained for the $\delta^{13}C$ linear mixing model. If the $\delta^{15}N$-based proportion of marine C was much lower than that calculated in the $\delta^{13}C$ model, this would indicate that the 'non-terrestrial' dietary component was of freshwater origin. The linear mixing model for $\delta^{15}N$ was constructed in a similar manner to the $\delta^{13}C$ model described above. For the 100% marine end member it was possible to use the averaged $\delta^{15}N$ values of the archaeofaunal samples. It was deemed impossible to use the archaeofaunal $\delta^{15}N$ values as an end member for a 100% terrestrial diet due to a very large scatter in the data. This is discussed in detail below. Instead, we elected to use the $\delta^{15}N$ of a human bone collagen sample that was highly likely, on the basis of $\delta^{13}C$ measurements, to represent a 100% terrestrial diet.

Calibrated age ranges, given to 95.4% (2σ) confidence intervals were calculated using OxCal version 4.1 (Bronk Ramsey, 1995, 2001). Firstly, a calibration was performed assuming 100% terrestrial carbon, using the atmospheric (IntCal09) calibration curve. The results thus obtained were compared with those obtained using a mixture of the atmospheric (IntCal09) and marine (Marine09) curves. The percentage marine C in the sample was obtained as described above, using the $\delta^{13}C$ stable isotope-mixing model. The ΔR used for calibration was based upon measured values for the north coast of Iceland in the Norse period ($+111 \pm 10$ ^{14}C years BP; Ascough et al., 2007).

3. Results

3.1 Stable isotopes

CN ratios of bone collagen can serve as an indicator of post-depositional degradation, or the addition of contaminants that may affect stable isotopic and radiocarbon measurement values. Although slight variations exist in the literature, CN values between 2.9-3.6 are generally accepted to show a low probability of post-depositional alteration in bone collagen (cf. DeNiro, 1985; Ambrose, 1990; Larsen et al., 1992) and the majority of samples measured in the present study have values within this range. Two cow bone samples (GU-14798 and GU-12083) and three cod bone samples (SUERC -24555, SUERC -24554 and SUERC -24553) have slightly higher CN values of 3.7-4.0. Two of the pig bone sample CN values (GU-15487

and GU-15486) are slightly low, at 2.7 and 2.8, respectively. Despite this, the $\delta^{13}C$ and $\delta^{15}N$ values of these samples are within the range of values obtained from equivalent samples with a CN ratio of 2.9-3.6, and inclusion of these samples does not affect values obtained for terrestrial or marine dietary resources used in palaeodietary reconstruction in this study.

The $\delta^{13}C$ and $\delta^{15}N$ ranges for human bone collagen samples were -19.9 to -16.4‰ and +7.7 to +14.2‰, respectively (Table 3). The $\delta^{13}C$ values for cattle bone collagen varied by 1.8‰ (-20.3 to -22.1‰), and that of caprines (sheep and goats) varied by 1.2‰ (-20.8 to -22.0‰). The $\delta^{15}N$ values of cattle bone collagen varied by 6.3‰ (-0.4 to +5.9‰), and that of caprine bone by 5.5‰ (-1.5 to +4.0‰). The average caprine $\delta^{15}N$ value is ~1‰ lower than for cow (0.5‰ (n=35) vs 1.6‰ (n=27)). The small sample of neonatal animals generally has higher $\delta^{15}N$ values than older animals, indicating suckling animals are effectively feeding at a higher trophic level than adults. Cow and caprine $\delta^{13}C$ and $\delta^{15}N$ values are comparable to values observed in other studies (e.g. Schoeninger and DeNiro, 1984), with no clear site-specific differences. It appears that variability due to age, sex, illness or the isotope values of food consumed by different animals at a single site is greater than variability between animals at different sites. The cow and caprine samples are taken as representative of the $\delta^{13}C$ and $\delta^{15}N$ values for terrestrial primary consumers for the study region.

Pig bone $\delta^{13}C$ and $\delta^{15}N$ values varied by 5.6‰ (-22.5 to -16.9‰) and by 9.9‰ (-1.2 to +8.7‰), respectively (Table 4). The $\delta^{13}C$ and $\delta^{15}N$ values of pigs from Hrísheimar are within the error range of those of the cow/caprine group, with two exceptions (GU-14806 and GU-12084). Four pigs at Sveigakot and six at Hofstaðir have $\delta^{13}C$ values that are heavier than those of the cow and caprine samples. Of these, the $\delta^{15}N$ of GU-15475 at Sveigakot (+8.7‰) and GU-13510 at Hofstaðir (+7.4‰) are also higher than the cow/caprine group. A further pig from Hofstaðir (GU-15276) has a $\delta^{15}N$ value of +6.6‰, which is at the upper end of the cow and caprine $\delta^{15}N$ range. These data suggest that at least some pigs within the sampled group may have consumed non-terrestrial resources. Omnivorous behavior is observed within modern pig populations, and has previously been identified in archaeological pig bone via stable isotope analyses (e.g. Greenfield, 1988, Müldner and Richards, 2005; Hamilton et al., 2009). To examine whether these resources were marine or freshwater, pigs with $\delta^{13}C$ values heavier than the cow/caprine samples were statistically analysed in the same way as the human bone samples, where the $\delta^{13}C$-based proportion of non-terrestrial protein and the $\delta^{15}N$-based proportion of marine protein were compared.

The freshwater fish bone $\delta^{13}C$ and $\delta^{15}N$ values vary by 3.8‰ (-12.2 to -16.0‰) and 1.2‰ (from +5.7 to +6.8‰) respectively (Table 4). The $\delta^{13}C$ range for marine material is 2.3‰ (-

12.4‰ to -14.7‰). The $\delta^{15}N$ values for these samples (fish and seal bone) cover a range of 2.2‰ (+13.1‰ to +15.3‰). The average $\delta^{13}C$ and $\delta^{15}N$ values for freshwater fish (n=6) are -14.7‰ and +5.9‰ respectively. For marine fish (n=16), average $\delta^{13}C$ and $\delta^{15}N$ values are -13.5‰ and +14.0‰ respectively. The isotope values for the seal bone are within the range of the marine fish.

3.2 Calculation of % marine C in human bone samples

The percentage of non-terrestrial carbon (assumed *a priori* to be of marine origin) within the human bone collagen samples was calculated via linear regression ($y = 270.67 + 13.333x$). The average $\delta^{13}C$ values for the terrestrial and marine archaeofaunal samples were used as end members, with a trophic level shift of +1‰ applied to the values. The calculated values for these $\delta^{13}C$ end members in our model compare very well with published values for both ancient and modern populations in the North Atlantic (Arneborg et al., 1999). The values for pig bone that fell outside the range for cow and caprine samples, and hence indicated a mixed diet, were not included in the terrestrial end member calculation.

Marine C percentages, calculated from regressions for the highest and lowest $\delta^{13}C$ values for the terrestrial and marine archaeofaunal samples (i.e. sensitivity analysis), showed an average variation of ± 13%. This is similar to the uncertainties used in previous studies (e.g. ± 10%; Sveinbjörnsdóttir et al., 2010). However, the variation was higher for samples with $\delta^{13}C$ values heavier than -18‰. We therefore used individual uncertainties on the calculated proportion of marine C for ^{14}C age calibration purposes.

The calculated percentage of marine carbon for the human bone and pig bone samples that showed heavier $\delta^{13}C$ values than those for the terrestrial primary consumers is shown in Table 5. The $\delta^{13}C$-based calculated proportion of marine C in the human bone collagen samples ranges from 6 ± 11% to 52 ± 19%. In the pig bones, the $\delta^{13}C$-based calculated proportion of marine C ranges from 3 ± 10% to 45 ± 18%.

3.3 ^{14}C ages and calibrated age ranges

The ^{14}C age of human bone samples (Table 3) ranged from 1075 ± 35 ^{14}C yr BP (SUERC-2027) to 1505 ± 35 ^{14}C yr BP (SUERC-2038). New measurements for cow and caprine faunal remains (Table 4) from sampled contexts range from 920 ± 35 ^{14}C yr BP (SUERC-11548) to 1160 ± 35 ^{14}C yr BP (SUERC-11547). This results in an overall 2σ age

range for the faunal remains of AD 972-1206, following calibration with the IntCal09 atmospheric calibration curve and OxCal v.4.1. The faunal dataset is therefore representative of the Viking period in Iceland.

The ^{14}C age measurements on human bone collagen suggest that in several instances, the ^{14}C age is highly likely to be influenced by a reservoir effect. Calibrated 2σ age ranges of the measured human bone ^{14}C ages obtained with the IntCal09 (i.e. terrestrial) calibration curve are given in Table 5. These range from AD 730-933 (SUERC-2666/SUERC-23338) to AD 435-639 (SUERC-2038). Thus, much of this range is prior to the conventional date for Viking *landnám*. Similarly, calibrated age ranges of the selected pig bone, obtained with IntCal09, indicate that a large reservoir effect is present in two of the three measured ages. These are AD 565-600 (GU-12080) and 394-206 BC (GU-13510). These pig bones were recovered from midden layers that accumulated significantly later than the *landnám* tephra of AD 871±2 (Lucas, 2010).

After calibration with the mixed IntCal09 and Marine09 curves, all except two of the calibrated ages of human bone samples post-date *landnám* (c. 870 AD). The exceptions are SUERC-2038 (444-807 AD), and SUERC-2016/SUERC-2660 (605-858 AD). The two pig bone ages (GU-12080 and GU-13510) still remain pre-*landnám* even after calibration with the mixed curve (Table 5).

3.4 Assessment of the potential for freshwater carbon incorporation into the bone samples

The percentage of marine carbon (relative to terrestrial/freshwater carbon) within the human and selected pig bone samples was calculated via linear regression ($y = -42.602 + 7.8786x$) using the average $\delta^{15}N$ values for the marine archaeofaunal samples as the 100% marine end members, with a trophic level shift of +4‰ applied to the values. We used the lowest $\delta^{15}N$ value from the human bone collagen samples, with insignificant marine protein input on the basis of the $\delta^{13}C$ model, as representative of human bone collagen $\delta^{15}N$ within this region for the Viking period and for individuals existing on an omnivorous diet of 100% terrestrial/freshwater protein. The results are shown in Table 5. Calculated proportions of non-terrestrial protein for the human bone samples are within the uncertainty limits of the proportion of marine protein calculated on the basis of $\delta^{13}C$ values. This suggests that either freshwater resources were not consumed by these individuals, or that the quantity of freshwater resources consumed was not significant enough to be resolved by the sensitivity of our analysis method. Application of the $\delta^{15}N$ mixing model to the pig bones shows that the

proportion of marine protein calculated on this basis is much lower than that calculated via the $\delta^{13}C$ values. This indicates that the majority of non-terrestrial protein consumed by the pigs was freshwater in origin.

4 Discussion

This work highlights the difficulties inherent in ^{14}C dating bone collagen from communities whose diets contained protein from multiple C reservoirs with varying ^{14}C reservoir effects. The issue of marine protein consumption with respect to the Marine ^{14}C Reservoir Effect (MRE) has been demonstrated at many sites globally (e.g. Arneborg et al., 1999; Richards and Sheridan, 2000; Petchey and Green, 2005; Petchey et al., 2011). However, the potential for freshwater protein to also impact upon ^{14}C ages is now also increasingly recognized (Cook et al., 2001; Bayliss et al., 2004; Fischer et al., 2007; Shishlina et al., 2007; Petchey et al., 2011). To obtain appropriate calendar age ranges for affected samples requires an ability to quantify the proportion of reservoir-affected C in a sample. This quantification must be credible, as use of an incorrect value for the amount of reservoir-affected C will result in the generation of inaccurate ^{14}C age ranges. A key problem in quantifying the amount of reservoir-affected (e.g. marine) C in a sample is that the $\delta^{13}C$ and $\delta^{15}N$ values of individuals of a single species feeding within the same reservoir show natural variation. For instance, $\delta^{13}C$ values in this study for terrestrial domesticated animals vary by 1.8‰, and those of marine/freshwater animals by 3.8‰. This range will be reflected in the tissues of consumers existing on these resources. An important point is that uncertainty within dietary reconstruction exists due to a range of other factors, such as the proportion of protein in the diet (Prowse et al., 2004, Keenleyside et al., 2006), or consumption of protein from organisms such as pigs, that have potentially consumed animal/fish products. In the case of archaeological samples it is also difficult to be certain that the isotopic baseline used in dietary reconstruction captures the full isotopic range of resources used by the population. For example, while large animal bones can remain in the archeological record for long periods of time and are easily recognized, small fish bones might go unnoticed in the absence of detailed sieving and other dietary components (certain plant foods) may leave no trace. For these reasons, a conservative approach to dietary reconstruction, with realistic uncertainties attached to calculated dietary proportions, is preferred. Because of this, it is clearly important to present calculated estimates of dietary components with attached estimates of uncertainty.

This decreases the precision to which we can resolve differences in individual diets but increases the probability that our values are accurate.

For human bone samples in this study, ^{14}C calibration with the mixed terrestrial/marine curve produces calibrated age ranges that are overall in better agreement with the date of *landnám*, and with pre-existing archaeological information. The samples from Gautlönd, Grímsstaðir and Glaumbær were apparently interred simultaneously with terrestrial mammals, providing a paired terrestrial ^{14}C age (Table 4) for these samples (McGovern et al., 2007; Ascough et al., 2010). The 2σ calibrated age ranges for the human bones generated from the mixed curve, using $\delta^{13}C$-based marine %C values, agree well with those of the paired terrestrial samples generated from IntCal09. These results suggest that the proportions of marine C calculated via the linear mixing model are of an acceptable degree of accuracy and precision in the majority of human bone samples. In two instances (Ytri-Neslönd and Víðar), the calibrated age ranges of the human bones obtained with the mixed curve pre-date *landnám*. One interpretation is that these interments genuinely reflect individuals present in Iceland prior to the accepted date of settlement. A second interpretation, favoured by the authors, is that the calibrated age ranges obtained for these individuals remain anomalously early, even when our $\delta^{13}C$-based proportions of marine protein consumption are taken into account. This is supported by the fact that the calibrated age range for a terrestrial mammal (horse) interred with the Ytri-Neslönd human is AD 772-937, and is hence consistent with *landnám* (Ascough et al., 2010). The mixed curve calibration brings the age of the human bone from this grave closer to that of the terrestrial age range, but clearly the correction is insufficient and the mixed curve calibrated age range remains anomalously low. At least two possibilities therefore remain to explain the ages of the Ytri-Neslönd and Víðar samples. Firstly, our $\delta^{13}C$-based calculation of the proportion of marine C present in the diet may still underestimate the actual proportion of marine C present. Secondly, there may be a freshwater dietary component in these samples that our methodology is unable to resolve. Although an archaeofaunal assemblage is not available for Ytri-Neslönd, this site is now located next to what are excellent char and trout fishing areas, and a freshwater component in the diet of earlier inhabitants at this location would not be surprising.

The latter hypothesis is strongly supported by the ^{14}C data from the pig samples that were deposited on the archaeological sites significantly after the *landnám* tephra fall of AD 871±2. Two of the pigs clearly display a ^{14}C reservoir effect greater than is possible if it were purely due to marine carbon, indicating these samples are affected by the large freshwater ^{14}C reservoir effect previously identified in the study area (Ascough et al., 2007, 2010). The $\delta^{13}C$

values for these samples suggest that a significant proportion of non-terrestrial carbon was consumed by these animals. The $\delta^{15}N$ values in these samples indicate that the majority of this non-terrestrial carbon was freshwater in origin, with the model suggesting up to 50% freshwater protein in one animal. This high proportion of freshwater resource consumption by certain pigs remains unexplained. Marine fish imports to inland Viking-period Icelandic sites appear to have undergone processing prior to transport that involved removal of the heads and mid-body vertebrae (McGovern et al., 2007); this may have meant that a larger proportion of freshwater fish was available to pigs feeding upon domestic waste. Unfortunately, it is only possible to state that the quantity of freshwater protein consumed was not larger than the uncertainty measure attached to the $\delta^{13}C$-based non-terrestrial protein values for these samples. The minimum uncertainty on the proportion of a calculated non-terrestrial dietary component is ± 11%. This is not an extreme measure, as it is similar to uncertainties identified in previous studies (e.g. Sveinbjörnsdóttir et al., 2010). This means that the resolution to which we are able to detect a freshwater protein component with this method is restricted to gross differences between individuals. The calibrated age ranges produced via the mixed terrestrial/marine calibration curve presented in this study must therefore be taken as minimum estimates due to the potential for the ^{14}C ages of these samples to be affected by a FRE that is not detectable via stable isotopic analyses. As previously highlighted, when a FRE is substantial, even a minor inclusion of dietary protein from this C reservoir is sufficient to shift the bone collagen ^{14}C ages considerably (Ascough et al., 2010). A further point is that the FRE within these samples could also result from the consumption of protein from pigs that have a large ^{14}C reservoir age. This would shift the human bone stable isotope values away from what would be expected if the human bone FRE resulted from direct consumption of freshwater resources. Consequently, it seems unwise to attempt any assessment of spatial variation in the chronology of pagan graves included in this study.

The results of this research have important implications within wider archaeological and palaeoenvironmental research fields. Large freshwater ^{14}C reservoir effects are not restricted to northern Icelandic settings and are now documented in a variety of environments, including inland rivers (Cook et al., 2001; Lillie et al., 2009); proglacial lakes (Hendy and Hall, 2006), and island lagoons (Spennemann and Head, 1998; Petchey et al., 2011). However appealing it may be to be able to correct bone ^{14}C ages for a FRE, it is increasingly apparent that achieving accurate FRE corrections is extremely complex. Identifying the presence of a freshwater component in bone collagen by stable isotope analysis is dependent upon sufficient isotopic separation between the freshwater and terrestrial dietary pools. The $\delta^{13}C$

signature of freshwater ecosystems can vary by ~20‰ between freshwater systems in different geographical locations (e.g. Post, 2002). Therefore, $\delta^{13}C$ values for freshwater resources frequently overlap with those of other resource pools, making accurate palaeodietary reconstructions complex (Tauber, 1981). When ^{14}C age measurement or palaeodietary studies are performed on animal or human bone, careful consideration is required as to whether a proportion of dietary resources could have been obtained from freshwater sources and whether these resources could display a FRE. If freshwater resources are separated isotopically from terrestrial resources in either of these isotopes, measurements of $\delta^{13}C$ and $\delta^{15}N$ together may provide a means to assess the potential for the incorporation of freshwater protein into the diet. This means that $\delta^{15}N$ measurements provide an inexpensive means of testing whether an individual is likely to have consumed a non-terrestrial dietary protein component (cf. Lanting and Van der Plicht, 1998; Cook et al., 2001). Knowledge is still required to characterize the $\delta^{15}N$ values of biota within the environments in question, as these may also vary. For example, Schoeninger et al. (1983) found $\delta^{15}N$ values of +6.6‰ to +9.5‰ in freshwater fish while Bonsall et al. (1997) recorded $\delta^{15}N$ values of +8.1 to +12.9‰ and $\delta^{13}C$ values of -15.7 to -26.3‰ in freshwater fish. A final complicating issue is that of temporal and spatial variability within FRE values themselves. As emphasised above, accurate ^{14}C age correction for C reservoir effects also requires an ability to accurately quantify the reservoir ^{14}C age offset. It is increasingly apparent that FRE values can vary by several thousand ^{14}C years between different systems and can also vary by this amount within individual systems (e.g. Ascough et al., 2010; Keaveny and Reimer, 2012).

5. Conclusions

The results reveal a significant non-terrestrial dietary component in samples of Norse Icelandic human and pig bone collagen. This substantially complicates ^{14}C dating because of the need to correct ages for both marine and freshwater ^{14}C reservoir effects. In this study, the $\delta^{13}C$ offset between potential dietary resources means we can readily separate terrestrial and non-terrestrial sample carbon, and ^{14}C age calibration with a mixed IntCal09/Marine 09 curve produces age ranges for human bone collagen that are more consistent with archaeological evidence than calibration with IntCal09. However, two of these ranges remain pre-*landnám*, and two bone collagen ages for pigs are several hundred years pre-*landnám*. The results strongly suggest that the $\delta^{13}C$-based marine ^{14}C age correction is insufficient to fully account for the reservoir-affected carbon in at least some samples.

In the study region, very large and variable freshwater ^{14}C reservoir effects exist and we believe the reason for the inaccuracies in the calibrated calendar age ranges of some pig and human bone samples is that some of the non-terrestrial carbon in the samples is of freshwater rather than marine origin. We can use $\delta^{15}N$ to assess the general proportions of freshwater carbon in the samples and in the pig bone samples we are confident that the majority of non-terrestrial carbon is freshwater in origin. In the human samples, we can only determine that the proportion of freshwater carbon is not greater than the uncertainty range associated with our calculated marine C proportions. The isotopic variation within the archaeofaunal data presented here highlights the need, during isotope-based dietary reconstructions, to obtain a fully representative set of samples of the dietary resources available to human populations. If the isotopic variability in resource groups is not captured, quantifications of ^{14}C reservoir-affected carbon, and hence corrected and calibrated ^{14}C age ranges, are likely to be inaccurate. The natural isotopic variability within a species population also means there should always be an uncertainty attached to stable-isotope based quantifications of dietary components.

Despite the limitations described above, the data reveal important information concerning Norse dietary and subsistence practices. The results emphasize the importance of marine resources in the diet of early Icelandic settlers, as even individuals buried far inland have a high marine dietary component. Pigs from the archaeological sites that were sampled clearly consumed a different diet to the humans found at pagan grave sites. This difference is most likely to be the result of higher trophic level freshwater resources being fed to the pigs. This could reflect a specific species-husbandry difference. However, measurements of bone collagen from human inhabitants of the archaeological sites are needed to confirm this.

Overall, the study indicates an early date for the Icelandic pagan grave inhabitants, which would be consistent with colonization of inland regions over a short time interval following the initial settlement of Iceland. The chronological resolution we can obtain is limited by an inability to correct for the freshwater ^{14}C reservoir-affected carbon. Although the presence of such carbon can be identified and quantified using stable isotopes, accurate ^{14}C age correction depends upon knowing the size of the ^{14}C reservoir effect to be corrected for. In Iceland, previous research shows FREs can vary by substantial amounts within and between systems, even at a single time period. This study therefore emphasizes that terrestrial samples are to be preferred for archaeological chronology construction wherever possible in order to avoid the uncertainties associated with ^{14}C reservoir effect correction.

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Table captions:

Table 1: Human bone samples included in this study. Site details are given in: [1]Eldjárn, 1948; [2]Eldjárn, 2000; [3]Gestsdóttir, 1998. Radiocarbon and stable isotope values for samples from Gautlönd, Grímsstaðir and Ytri-Neslönd are previously published in [*]McGovern et al., 2007 and/or [†]Ascough et al., 2010.

Table 2: Archaeological sites and contexts from which material was obtained for this study.

Table 3: Radiocarbon and stable isotope measurements of human bone collagen from graves included in this study. Radiocarbon and stable isotope values for samples from Gautlönd, Grímsstaðir, Ytri-Neslönd and Glaumbær are previously published in [*]McGovern et al., 2007 and/or [†]Ascough et al., 2010. [a]$\delta^{13}C$ measurements used for normalization of measured sample $^{14}C/^{13}C$ ratios to values corresponding to $\delta^{13}C$ = -25‰.

Table 4: Radiocarbon and stable isotope measurements of faunal bone collagen from archaeological sites included in this study. Samples where measurements have been published previously are indicated: [*]McGovern et al, 2007; [‡]Ascough et al., 2007; [†]Ascough et al., 2010; [§]Russell et al., 2011. [**]Post-dates 10th century Veiðivötn tephra layer. [a]$\delta^{13}C$ measurements used for normalization of measured sample $^{14}C/^{13}C$ ratios to values corresponding to $\delta^{13}C$ = -25‰.

Table 5: Sample calibrated age ranges obtained with the atmospheric IntCal09 curve (i.e. 0% marine carbon) and calibrated age ranges obtained with a mixed IntCal09/Marine09 curve. For the mixed curve approach, $\Delta R = 111 \pm 10$ ^{14}C yr BP, and sample % marine carbon was obtained via the measured $\delta^{13}C$.

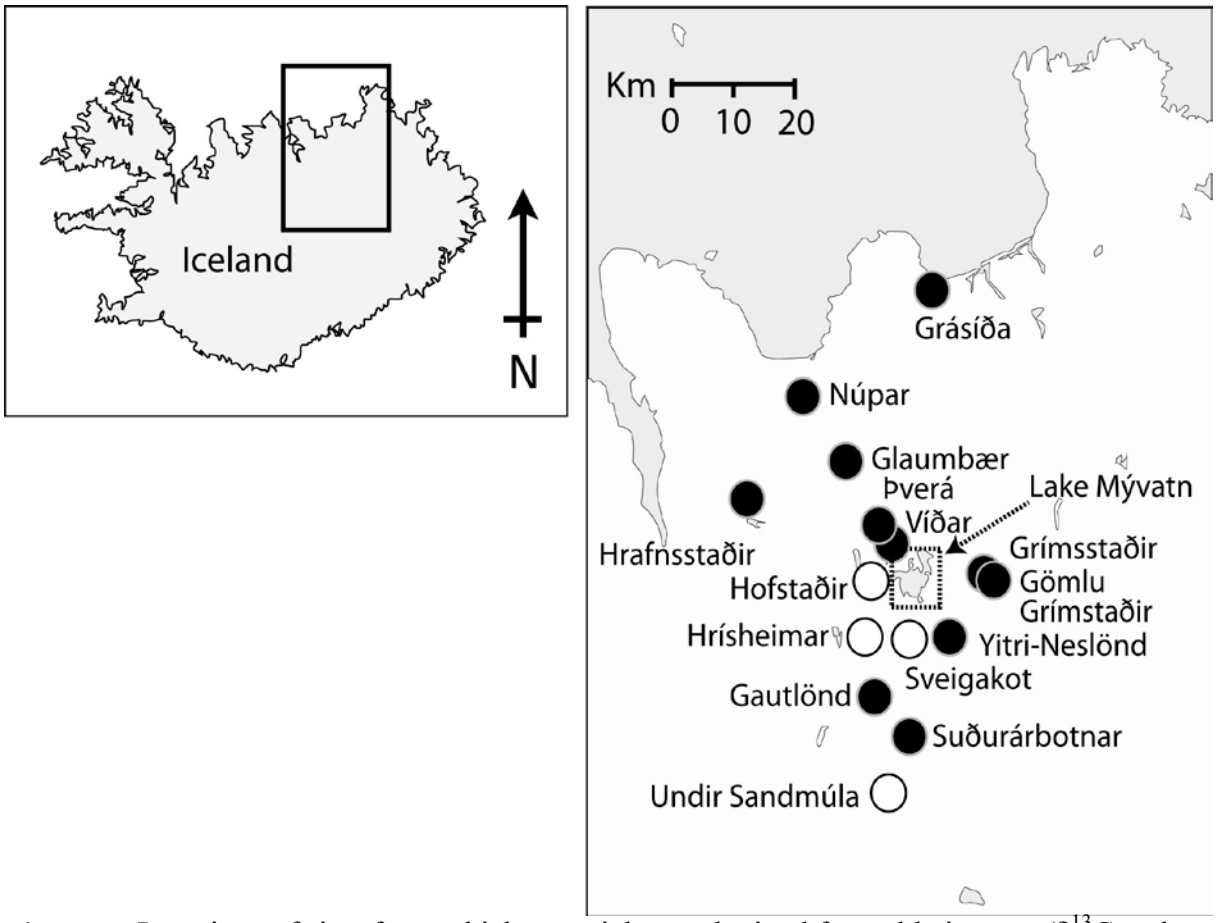

Figure 1: Locations of sites from which material was obtained for stable isotope ($\delta^{13}C$ and $\delta^{15}N$) and radiocarbon (^{14}C) measurement. Left hand image indicates the study area within Iceland. Pagan grave sites are indicated by black circles, archaeofaunal sampling sites are indicated by white circles.

Site	Sample ID	Year of excavation	Sex/Age
Grásíða	GSV-A-1	1941	Male, 18-25[1,2,3]
Gömlu Grímsstaðir	GRF-A-1	1962	Indeterminate (Adult)[2]
Hrafnsstaðir	HRK-A-1	1952	Probable male, >45[2,3]
Núpar	NUA-A-1	1915	Probable female, 35-35[2]
Suðurárbotnar,	SUB-A-1	1947	Male 18-25[2,3]
Þverá	2000-3-1	1985	Indeterminate[2]
Víðar	MKR-A-1	1989	Male, >50[2]
Gautlönd[*,†]	GLÞ-A-1	1855	Male, >45[2]
Grímsstaðir[*,†]	GRS-A-1	1967	Male, 35-45[2]
Ytri-Neslönd[*,†]	YNM-A-1	1960	Male, Adult[2]
Glaumbær[†]	GBR-A-2	1915	Male, >45[2,3]

Table 1: Human bone samples included in this study. Site details are given in: [1]Eldjárn, 1948; [2]Eldjárn, 2000; [3]Gestsdóttir, 1998. Radiocarbon and stable isotope values for samples from Gautlönd, Grímsstaðir and Ytri-Neslönd are previously published in [*]McGovern et al., 2007 and/or [†]Ascough et al., 2010.

Site	Location	Description	Contexts sampled
Undir Sandmúla	65°12' N 17°20' W	Indeterminate-status farmstead	Single discreet midden layer overlying 10th century Veiðivötn tephra and are directly ^{14}C dated to 10th-11th centuries cal AD (McGovern, 2005).
Sveigakot	65°30' N 17°01' W	Low-status farmstead	Single discreet midden layer overlying 10th century Veiðivötn tephra and are directly ^{14}C dated to 10th-11th centuries cal AD (Vésteinsson, 2002).
Hofstaðir	65° 61' N 17° 16' W	High-status farmstead	Multiple midden layers and occupation layers (floor levels, hearth fills, pit fills) that overlie a 10th century Veiðivötn tephra and are directly ^{14}C dated to 10th-11th centuries cal AD (Lucas, 2010).
Hrísheimar	65° 52' N 17° 10' W	Indeterminate-status farmstead	Multiple midden layers that overlie both the landnám tephra (871±2 AD) and a 10th century Veiðivötn tephra and are directly ^{14}C dated to 9th-11th centuries cal AD (Edvardsson and McGovern, 2007).

Table 2: Archaeological sites and contexts from which material was obtained for this study.

Sample No.	**Reporting No.**	**Site**	**Species**	**$\delta^{13}C$ (‰)**	**$\delta^{15}N$ (‰)**	**C/N**	**$\delta^{13}C$ (‰) for ^{14}C AMS[a]**	**^{14}C age BP**
GRF-A-1	SUERC-2033	Gömlu Grímsstaðir	Human	-18.4	11.0	3.1	-18.5	1210 ± 35
GSV-A-1	SUERC-2666	Grásíða	Human	-19.6	7.4	3.1	-19.9	1225 ± 35
	SUERC-23338	Grásíða	Human	-20.1	7.9	3.3	-20.1	1175 ± 25
	Weighted mean			-19.9	7.7			1192 ± 24
HRK-A-1	SUERC-2034	Hrafnsstaðir	Human	-19.5	10.8	3.1	-19.6	1215 ± 35
NUA-A-1	SUERC-2023	Núpar	Human	-17.3	12.6	3.2	-17.8	1260 ± 35
SUB-A-1	SUERC-2037	Suðurárbotnar	Human	-16.4	14.2	3.0	-17.2	1305 ± 35
2000-3-1	SUERC-2039	Þverá	Human	-19.7	8.7	3.1	-19.9	1235 ± 35
MKR-A-1	SUERC-2038	Víðar	Human	-18.4	9.2	3.1	-18.6	1505 ± 35
Previously published data								
	Reporting No.	**Site**	**Species**	**$\delta^{13}C$ (‰)**	**$\delta^{15}N$ (‰)**	**C/N**	**$\delta^{13}C$ (‰)**	**^{14}C age BP**
GLÞ-A-1	SUERC-2026/SUERC 2663[*,†]	Gautlönd	Human	-19.6	8.1	3.0	-20.7	1188 ± 25
GRS-A-1	SUERC-2018 [*,†]	Grímsstaðir	Human	-19.3	10.0	3.1	-19.8	1225 ± 35
YNM-A-1	SUERC-2016/SUERC 2660 [*,†]	Ytri-Neslönd	Human	-19.1	9.0	3.1	-19.4	1400 ± 25
GBR-A-2	SUERC-2028[†]	Glaumbær	Human	-19.4	9.7	3.1	-19.8	1155 ± 35

Table 3: Radiocarbon and stable isotope measurements of human bone collagen from graves included in this study. Radiocarbon and stable isotope values for samples from Gautlönd, Grímsstaðir, Ytri-Neslönd and Glaumbær are previously published in [*]McGovern et al., 2007 and/or [†]Ascough et al., 2010. [a]$\delta^{13}C$ measurements used for normalization of measured sample $^{14}C/^{13}C$ ratios to values corresponding to $\delta^{13}C$ = -25‰.

Reporting No.	Site	Context No.	Species	δ ^{13}C	δ ^{15}N	C/N	δ^{13}C for ^{14}C AMS[a]	^{14}C age BP
GU-14455	Undir Sandmúla	2	Cow adult	-21.6	2.1	3.4	-21.5	920 ± 35
GU-14456	Undir Sandmúla	2	Cow adult	-21.6	0.1	3.6	-21.9	1040 ± 35
GU-14798	Undir Sandmúla	2	Cow adult	-22.0	2.4	3.9	-	-
GU-14799	Undir Sandmúla	2	Caprine adult	-21.3	-1.3	3.3	-	-
GU-14800	Undir Sandmúla	2	Caprine adult	-21.4	-0.2	3.5	-	-
GU-14801	Undir Sandmúla	2	Caprine adult	-21.3	-0.8	3.5	-	-
GU-14802	Undir Sandmúla	2	Caprine adult	-21.5	-1.0	3.6	-	-
GU-14803	Undir Sandmúla	2	Goat adult	-21.4	-1.0	3.3	-	-
GU-15461	Sveigakot	55	Cow adult	-21.5	1.2	3.2	-	-
GU-15462	Sveigakot	55	Cow adult	-21.3	0.2	3.3	-	-
GU-15463	Sveigakot	55	Cow adult	-22.1	0.3	3.3	-	-
GU-15464	Sveigakot	55	Cow adult	-21.3	0.9	3.3	-	-
GU-15465	Sveigakot	55	Cow neonatal	-20.9	2.3	3.4	-	-
GU-15466	Sveigakot	55	Cow neonatal	-21.2	2.1	3.5	-	-
GU-15467	Sveigakot	55	Caprine juvenile	-21.1	0.0	3.3	-	-
GU-15468	Sveigakot	55	Caprine adult	-21.1	-0.6	3.4	-	-
GU-15469	Sveigakot	55	Caprine adult	-21.1	0.3	3.3	-	-
GU-15470	Sveigakot	55	Caprine juvenile	-21.5	0.4	3.6	-	-
GU-15471	Sveigakot	55	Caprine adult	-21.3	0.0	3.3	-	-
GU-15472	Sveigakot	55	Caprine adult	-21.1	-0.3	3.3	-	-
GU-15473	Sveigakot	55	Pig juvenile	-19.8	3.0	3.5	-	-
GU-15474	Sveigakot	55	Pig juvenile	-21.3	0.2	3.3	-	-
GU-15475	Sveigakot	55	Pig juvenile	-17.8	8.7	3.4	-	-
GU-15476	Sveigakot	55	Pig neonatal	-21.3	2.0	3.5	-	-
GU-15477	Sveigakot	55	Pig adult	-20.4	3.3	3.4	-	-
GU-15478	Sveigakot	55	Pig adult	-21.5	3.0	3.3	-	-
GU-15485	Sveigakot	55	Pig adult	-20.6	4	3.2	-	-
GU-15486	Sveigakot	55	Pig adult	-21.5	1.8	2.8	-	-
GU-15487	Sveigakot	55	Pig adult	-21.1	1.3	2.7	-	-
GU-13508	Hofstaðir	233	Caprine adult	-21.7	0.7	3.4	-21.6	990 ± 35
GU-13509	Hofstaðir	254	Caprine adult	-21.3	1.1	3.2	-21.4	1035 ± 35
GU-13511	Hofstaðir	254	Sheep adult	-21.8	0.1	3.3	-21.8	1040 ± 35
GU-13512	Hofstaðir	170	Caprine adult	-21.4	1.3	3.2	-21.4	1050 ± 35
GU-13624	Hofstaðir	6n	Cow adult	-21.2	1.4	3.2	-21.0	1110 ± 40
GU-13625	Hofstaðir	6n	Cow adult	-21.0	2.6	3.3	-20.9	1110 ± 30
GU-13626	Hofstaðir	6n	Cow adult	-21.2	0.1	3.1	-21.1	1130 ± 35
GU-13627	Hofstaðir	6n	Cow adult	-21.4	-0.2	3.3	-21.2	1080 ± 35
GU-14451	Hofstaðir	2428	Caprine adult	-21.3	0.4	3.6	-21.3	1030 ± 35
GU-14452	Hofstaðir	448	Sheep adult	-20.9	0.6	3.4	-20.8	1040 ± 35
GU-14453	Hofstaðir	1480	Sheep adult	-21.0	1.1	3.3	-20.9	1075 ± 35

GU-14454	Hofstaðir	76	Caprine adult	-21.4	1.8	3.4	-21.3	1160 ± 35
GU-14804	Hofstaðir	1495	Cow adult	-21.5	0.2	3.5	-	-
GU-14805	Hofstaðir	1166	Sheep adult	-21.5	1.4	3.3	-	-
GU-15267	Hofstaðir	6m	Caprine neonatal	-21.3	4.0	3.1	-	-
GU-15268	Hofstaðir	6m	Caprine neonatal	-21.5	2.5	3.1	-	-
GU-15269	Hofstaðir	6m	Caprine juvenile	-21.0	0.5	3.1	-	-
GU-15270	Hofstaðir	6m	Caprine adult	-20.9	1.6	3.1	-	-
GU-15271	Hofstaðir	6m	Caprine adult	-20.8	1.2	3.1	-	-
GU-15272	Hofstaðir	6m	Caprine adult	-21.0	0.2	3.1	-	-
GU-15273	Hofstaðir	6n	Pig neonatal	-21.7	4.4	3.3	-	-
GU-15274	Hofstaðir	6n	Pig neonatal	-21.2	0.9	3.3	-	-
GU-15275	Hofstaðir	6n	Pig adult	-21.3	1.8	3.3	-	-
GU-15276	Hofstaðir	6n	Pig juvenile	-18.9	6.6	3.4	-	-
GU-15277	Hofstaðir	6n	Pig juvenile	-21.5	0.3	3.1	-	-
GU-15278	Hofstaðir	6n	Pig adult	-21.3	3.1	3.3	-	-
GU-12083	Hrísheimar	2	Cow adult	-22.0	2.0	3.9	-21.5	1095 ± 35
GU-12085	Hrísheimar	60	Cow neonatal	-20.9	1.5	3.2	-20.9	1090 ± 35
GU-14806	Hrísheimar	429	Pig adult	-20.6	3.9	3.5	-	-
GU-14807	Hrísheimar	429	Cow neonatal	-20.4	3.1	3.4	-	-
GU-14808	Hrísheimar	429	Cow adult	-21.6	2.3	3.3	-	-
GU-14809	Hrísheimar	429	Sheep adult	-21.0	1.6	3.4	-	-
GU-15279	Hrísheimar	3	Pig neonatal	-22.5	-1.2	3.4	-	-
GU-15280	Hrísheimar	3	Pig neonatal	-22.2	-0.7	3.5	-	-
GU-15281	Hrísheimar	3	Pig neonatal	-21.8	0.0	3.3	-	-
GU-15282	Hrísheimar	3	Pig adult	-22.2	-0.4	3.5	-	-
GU-15283	Hrísheimar	3	Pig adult	-22.0	-0.5	3.3	-	-
GU-15284	Hrísheimar	3	Pig adult	-21.3	0.1	3.2	-	-
GU-15285	Hrísheimar	3	Pig adult	-21.9	-0.6	3.3	-	-
GU-15286	Hrísheimar	3	Sheep adult	-21.2	-0.5	3.3	-	-
GU-15287	Hrísheimar	3	Sheep adult	-21.0	0.9	3.3	-	-
GU-15288	Hrísheimar	3	Sheep adult	-21.3	0.6	3.4	-	-
GU-15289	Hrísheimar	3	Sheep adult	-21.1	1.6	3.2	-	-
GU-15290	Hrísheimar	3	Sheep adult	-22.0	1.7	3.6	-	-
GU-15291	Hrísheimar	3	Sheep adult	-21.2	-0.2	3.3	-	-
GU-15292	Hrísheimar	3	Sheep adult	-21.2	0.6	3.2	-	-
GU-15293	Hrísheimar	3	Sheep adult	-21.3	-1.5	3.3	-	-
GU-15294	Hrísheimar	3	Sheep adult	-21.6	0.3	3.4	-	-
Previously published data								
SUERC-3429[*,†]	Hofstaðir	7a	Cow neonatal	-21.0	5.9	3.1	-21.2	1160 ± 35
SUERC-3430[*,†]	Hofstaðir	7a	Pig adult	-21.0	4.6	3.4	-20.8	1170 ± 40
SUERC-3431[*,†]	Hofstaðir	6d	Cow neonatal	-20.3	1.6	3.1	-18.8	1045 ± 35
SUERC-3432[*,†]	Hofstaðir	6d	Pig adult	-21.5	0.5	3.5	-21.5	1040 ± 40
SUERC-3433[*,†]	Hofstaðir	6g	Cow adult	-20.9	3.8	3.3	-21.1	1030 ± 35
SUERC-	Hofstaðir	6g**	Pig juvenile	-19.8	3.7	3.2	-20.0	1430 ± 35

3438[*,†]								
SUERC-8355[c]	Hofstaðir	254**	Pig adult	-16.9	7.4	3.2	-16.9	2250 ± 35
SUERC-11539[†]	Hofstaðir	6ij**	Arctic charr	-12.5	5.7	3.4	-12.4	4930 ± 35
SUERC-11540[†]	Hofstaðir	6ij**	Brown trout	-12.2	6.8	3.5	-11.8	4675 ± 35
SUERC-3439[*,†]	Hrísheimar	3	Cow neonatal	-20.9	2.3	3.3	-21.1	1085 ± 35
SUERC-3440[*,†]	Hrísheimar	3	Pig juvenile	-21.3	0.1	3.1	-21.4	1150 ± 40
SUERC-3442[*,†]	Hrísheimar	2	Pig juvenile	-20.1	1.3	3.1	-20.2	1120 ± 35
SUERC-3446[*,†]	Hrísheimar	2	Cow neonatal	-21.4	1.0	3.1	-21.5	1080 ± 35
SUERC-6431[‡]	Hrísheimar	45	Cow adult	-21.7	-0.4	3.2	-21.5	1220 ± 35
SUERC-6432[‡]	Hrísheimar	45	Cow adult	-21.6	1.5	3.2	-21.4	1200 ± 35
SUERC-6433[‡]	Hrísheimar	45	Cow adult	-21.8	0.0	3.2	-21.7	1120 ± 35
SUERC-6437[‡]	Hrísheimar	45	Cow adult	-20.9	1.8	3.2	-20.7	1120 ± 35
SUERC-9045[‡]	Hrísheimar	45	Arctic charr	-15.9	6.0	3.1	-15.2	2626 ± 40
SUERC-9049[‡]	Hrísheimar	45	Arctic charr	-16.0	5.7	3.3	-15.5	2505 ± 40
SUERC-9050[‡]	Hrísheimar	45	Arctic charr	-15.5	5.6	3.2	-15.0	2950 ± 35
SUERC-9051[‡]	Hrísheimar	45	Arctic charr	-15.9	5.8	3.2	-15.3	2670 ± 35
SUERC - 24553[§]	Roberts Haven	3004	Atlantic cod	-14.7	13.5	4.0	-14.4	1187 ± 30
SUERC - 24554[§]	Roberts Haven	3004	Atlantic cod	-14.1	15.3	3.8	-13.8	1115 ± 30
SUERC - 24555[§]	Roberts Haven	3004	Atlantic cod	-13.7	13.7	3.7	-13.6	1157 ± 30
SUERC - 24556[§]	Roberts Haven	3004	Atlantic cod	-13.4	13.9	3.6	-13.4	1167 ± 30
SUERC - 24560[§]	Roberts Haven	3019	Atlantic cod	-14.4	15.0	3.6	-14.3	1229 ± 30
SUERC - 24561[§]	Roberts Haven	3019	Atlantic cod	-12.5	13.1	3.5	-12.4	1280 ± 30
SUERC - 24562[§]	Roberts Haven	3019	Atlantic cod	-13.3	15.3	3.4	-13.2	1270 ± 30
SUERC - 24563[§]	Roberts Haven	3019	Atlantic cod	-13.3	14.0	3.4	-13.1	1315 ± 30
SUERC - 24564[§]	Quoygrew	A004	Atlantic cod	-12.9	13.9	3.5	-12.6	1251 ± 30
SUERC - 24565[§]	Quoygrew	A004	Atlantic cod	-14.3	13.7	3.6	-14.0	1230 ± 30
SUERC - 24566[§]	Quoygrew	A004	Atlantic cod	-14.2	14.9	3.5	-13.9	1181 ± 30
SUERC - 24570[§]	Quoygrew	A004	Atlantic cod	-13.7	13.7	3.5	-13.3	1210 ± 30
SUERC - 24571[§]	Quoygrew	A023	Atlantic cod	-12.4	14.2	3.3	-12.0	1287± 30
SUERC - 24572[§]	Quoygrew	A023	Atlantic cod	-13.0	13.6	3.4	-12.7	1283 ± 30
SUERC - 24573[§]	Quoygrew	A023	Atlantic cod	-13.4	13.1	3.3	-13.0	1246 ± 30
SUERC -	Quoygrew	A023	Atlantic cod	-13.0	13.8	3.4	-13.8	1256 ± 30

24574[§]								
SUERC-8633[‡]	Gásir	528	Seal	-12.7	+14.4	3.2	-12.7	1115 ± 40
SUERC-2664 [*,†] SUERC-2352 [*,†]	Gautlönd	Grave containing human sample GLÞ-A-1	Dog Dog	-20.5 -20.5	8.3 n/a	2.9 n/a	-20.2 -20.5	1175 ± 35 1170 ± 40 Weighted mea 1173 ± 26
SUERC-2019[*,†] SUERC-2662[*,†]	Grímsstaðir	Grave containing human sample GRS-A-1	Horse Horse	-21.0 -20.7	1.7 1.2	3.1 3.0	-21.2 -20.9	1145 ± 35 1105 ± 35 Weighted mea 1125 ± 25
SUERC-2017[*,†] SUERC-2661[*,†]	Ytri-Neslönd	Grave containing human sample YNM-A-1	Horse Horse	-21.8 -21.7	2.7 2.0	3.2 3.1	-22.3 -21.5	1175 ± 35 1200 ± 35 Weighted mea 1188 ± 25
SUERC-2029[†] SUERC-2670[†]	Glaumbær	Grave containing human sample GBR-A-2	Horse Horse	-21.3 -21.5	3.4 n/a	3.1 n/a	-21.4 -21.5	1185 ± 35 1115 ± 35 Weighted mea 1150 ± 25

Table 4: Radiocarbon and stable isotope measurements of faunal bone collagen from archaeological sites included in this study. Samples where measurements have been published previously are indicated: [*]McGovern et al, 2007; [‡]Ascough et al., 2007; [†]Ascough et al., 2010; [§]Russell et al., 2011. [**]Post-dates 10[th] century Veiðivötn tephra layer. [a]$\delta^{13}C$ measurements used for normalization of measured sample $^{14}C/^{13}C$ ratios to values corresponding to $\delta^{13}C$ = -25‰.

Human bone						
Reporting No.	**Site**	**2σ calibrated range BC/AD**	**% Marine C (via $\delta^{13}C$)**	**2σ calibrated range BC/AD (Mixed curve)**	**% Marine C (via $\delta^{15}N$)**	**Offset ($\delta^{13}C$-$\delta^{15}N$)**
SUERC-2033	Gömlu Grímsstaðir	689-894 AD	25 ± 14	723-1122 AD	32 ± 3	+7
SUERC-2666/SUERC-23338	Grásíða	730-933 AD	6 ± 11	733-936 AD	0 ± 0	-6
SUERC-2034	Hrafnsstaðir	689-891 AD	11 ± 11	690-995 AD	30 ± 3	+19
SUERC-2023	Núpar	668-869 AD	40 ± 17	725-1164 AD	47 ± 5	+7
SUERC-2037	Suðurárbotnar	655-775 AD	52 ± 19	725-1192 AD	63 ± 7	+11
SUERC-2039	Þverá	686-881 AD	8 ± 11	683-970 AD	10 ± 1	+2
SUERC-2038	Víðar	435-639 AD	25 ± 14	444-807 AD	15 ± 2	-10
SUERC-2026/SUERC 2663	Gautlönd	772-937 AD	9 ± 11	722-1016 AD	4 ± 0	-5
SUERC-2028	Glaumbær	778-972 AD	12 ± 12	725-1048 AD	20 ± 2	+8
SUERC-2018	Grímsstaðir	688-887 AD	13 ± 12	689-997 AD	22 ± 2	+9
SUERC-2016/SUERC 2660	Ytri-Neslönd	604-665 AD	16 ± 12	605-858 AD	13 ± 1	-3
Pig bone						
GU-12084	Hrísheimar	782-1013 AD	3 ± 10	778-1024 AD	-61 ± 6	-63
GU-15473	Sveigakot	-	7 ± 11	-	-49 ± 5	-51
GU-12080	Hofstaðir	565-600 AD	7 ± 11	542-770 AD	-42 ± 4	-44
GU-15276	Hofstaðir	-	19 ± 13	-	-11 ± 1	-29
GU-15475	Sveigakot	-	33 ± 15	-	11 ± 1	-23
GU-13510	Hofstaðir	394-206 BC	45 ± 18	BC 353 – 129 AD	-3 ± 0	-48

Table 5: Sample calibrated age ranges obtained with the atmospheric Intcal09 curve (i.e. 0% marine carbon) and calibrated age ranges obtained with a mixed Intcal09/Marine09 curve. For the mixed curve approach $\Delta R = 111 \pm 10$ ^{14}C yr BP, and sample % marine carbon was obtained via the measured $\delta^{13}C$.